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Conglomerate recycling in the Himalayan foreland basin: Implications for grain size and provenance.

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ABSTRACT

The nature of coarse sediment in rivers emerging from mountain ranges determines rates of downstream fining, the position of the gravel-sand transition, sediment entrainment thresholds and channel morphologies. Additionally, in the stratigraphic record, clast size distributions and lithologies are used to reconstruct paleo-hydraulic conditions and source area provenance. Using Himalayan rivers, we demonstrate that the signal of first-generation clasts derived from the hinterland of a mountain range can be significantly altered by recycling older, structurally exhumed foreland deposits. The Siwalik foothills of the Himalaya comprise Neogene fluvial sandstones and quartzite-rich conglomerates with well-rounded clasts that were deposited in the Indo-Gangetic foreland basin and later exhumed by erosion, following uplift along the Himalayan mountain front. Mass balance calculations reveal that the Upper Siwalik conglomerate may contribute a significant proportion of the total gravel flux exported from the main Himalayan catchments (up to 100%) despite forming <1% of the catchment geology. Three end-member catchments with variable proportions of gravel flux from Siwalik conglomerates are analyzed to test for the effects of conglomerate recycling. Catchments that recycle the most Upper Siwalik conglomerate form quartzite-rich gravel bars comprising well-rounded pebbles and a

narrow grain size distribution, mimicking the characteristics of the Upper Siwalik conglomerate. Conversely, catchments that recycle the least Upper Siwalik conglomerate form gravel bars with a range of Himalayan lithologies, angular quartzite pebbles and a wider grain size distribution. This study highlights that recycling of quartzite-rich conglomerate can dramatically modify the flux, lithology, grain size and shape of gravel entering the Indo-Gangetic Plain.

INTRODUCTION

River catchments that drain the Himalaya are characterized by relatively small (<1,000 km^2) 'foothill-fed' river catchments interspersed between much larger (>50,000 km^2) 'mountain-fed' catchments that are sourced from the high glaciated peaks that lie at the transition with the Tibetan Plateau to the north (Sinha and Friend, 1994). Despite significant variations in catchment size, source area lithology and erosion rates, it has been observed that the flux of gravel (mass/year) into the Plains is broadly similar for all catchments (Dingle et al. 2017). The observed high proportion of quartzite clasts compared to other Himalayan lithologies (e.g. gneiss, granite, schist etc.) in river gravels, combined with numerical modelling of pebble abrasion for different Himalayan lithologies (Attal and Lavé, 2006), led Dingle et al. (2017) to conclude that most of the gravel supplied to the large catchments of the Himalaya is abraded and converted into sand and finer sediment before it reaches the Ganga Plain. The disproportionate dominance of quartzite clasts is also recorded in the conglomerates of the thick Miocene and Pliocene Upper Siwalik formations that dominate the frontal foothills of the Himalaya (Kumar et al. 2003; Dubille and Lavé, 2015). If abrasion limits the delivery of gravel from large mountain-fed rivers, then what impact does the recycling of Siwalik conglomerates have in modifying grain size distributions and enhancing the flux of gravel delivered to the Gangetic Plains?

Many aspects of modern rivers draining mountain ranges and their stratigraphic equivalents are determined by grain size characteristics delivered from source regions. River stability and morphology depend on the balance between the magnitude and grain size characteristics of the sediment supplied from the hinterland and the spatial distribution of accommodation space generated by subsidence (Paola et al. 1992; Dade and Friend, 1998; Fedele and Paola, 2007; Duller et al. 2010; Allen et al. 2013). Changes in gravel flux drive the migration of the gravel front further out into subsiding foreland basins, leading to pulses of conglomerate progradation in the stratigraphic record (Paola et al. 1992; Burbank, 1992). Conglomeratic beds observed in the Kangra Siwalik succession (north-west India) exemplify this phenomenon, whereby the initiation of the Main Boundary Thrust caused a localized increase in the gravel flux, causing the gravel front to prograde further into the basin (Meigs et al. 1995; Brozovic and Burbank, 2000). The rate of downstream fining from the mountain front to the gravel front also depends on the grain size distribution supplied from the upland source region (Duller et al. 2010). Further downstream, the transition from a gravel-dominated river to sand-dominated (the gravel-sand transition) is commonly associated with a change in channel morphology from braided to meandering (Dubille and Lavé, 2015). This transition also controls river stability, whereby the grain size distribution of the sediment forming river bed and banks locally determines rates of river migration, as alluvial rivers adjust their geometry to the threshold-limiting bed and bank material (Thorne and Tovey, 1981; Dunne and Jerolmack, 2017).

The role of sediment recycling in modifying the characteristics and flux of gravel to foreland basins has been reported from a number of settings. Youngson and Craw (1996) observed multiple quartzite rich conglomerate beds in Otago (New Zealand), which they attribute to lithological dilution through recycling, where the strongest lithology (quartzite) survived the recycling process and therefore dominates the stratigraphy. Colombo (1994) suggested that conglomerates outcropping in Serra de La Llena (north-east Spain) were formed from repeated recycling and unroofing of older alluvial gravels, producing a series of conglomerate beds that display progressive dilution of the original source area lithologies up section. Schlunegger and Mosar (2011) attributed an increase in sediment flux at the Miocene-Pliocene boundary in the central basins of the Alps to the recycling of ancient molasse units. Analysis of cosmogenic ^{21}Ne from pebbles of the modern North Platte River of Nebraska demonstrates that the majority of the coarse gravel of the river has experienced long periods (10^5 to $>10^6$ yrs) of floodplain storage and recycling, which explain the presence of pebbles hundreds of kilometers into the Great Plains (Sinclair et al. 2019). Also, it has been demonstrated that there is a strong correlation between the degree of recycling of alluvial fans and the coarseness of three alluvial fans in the Iglesia Basin of Central Argentina (Harries et al. 2019). However, most of these studies are based on the interpretation of old sedimentary series and, to date, there hasn't been a clear demonstration of the impact of recycling on the characteristics of the sediment (flux, shape, grain size distribution) exported by rivers, in particular with reference to modern river systems.

The Siwalik Group forms the frontal foothills of the Himalaya and comprises Neogene fluvial sandstones and quartzite-rich conglomerates which were deposited in the Indo-Gangetic foreland basin during Miocene-Pliocene times and later exhumed by erosion following thin-skinned tectonics and the southward propagation of the Himalayan deformation (Hérail and Mascle, 1980; Burbank, 1996; Mugnier et al. 1999). The Siwalik Group comprises an upward coarsening fluvial mega-sequence, and is traditionally subdivided into the Lower-, Middle-, and Upper Siwalik subgroups based on dominant facies (Shah, 1977; Hérail and Mascle, 1980; Jian and Sinha, 2003; Kumar et al. 2003). Conglomerates form the Upper Siwalik subgroup which typically accounts for less than 1% of the rock types exposed in the large mountain-fed river catchments (Schelling, 1992; Rautela and Sati, 1996; Mugnier et al. 1999; Yin 2006; Goswami and Deopa, 2015). The conglomerates comprise poorly consolidated, massive to upward fining cycles of sub-rounded to rounded clasts (Kumar et al. 2003). The dominant clast lithology is quartzite (70-90 %) and individual clasts can vary from pebble to boulder size (Brozovic and Burbank, 2000; Kumar et al. 2003; Dubille and Lavé, 2015).

There is evidence to suggest that the recycling of Siwalik conglomerates may play a role in defining the grain size distribution and lithological content of gravel delivered to the Gangetic Plains. Sediment in foothill-fed rivers draining the Siwalik Hills south of Kathmandu displays median grain sizes similar to that of the Siwalik sedimentary rock source (Dubille and Lavé, 2015); meanwhile, mountain-fed river gravel bars exhibit high proportions of quartzite pebbles, compared to the other Himalayan lithologies exposed in their catchments (Dingle et al. 2017). Furthermore, Siwalik sediment recycling has been suggested to explain the unusually long lag times (5.2 Myr) observed in detrital apatite fission-track (AFT) studies from the Surai Khola section of the Siwalik Group, in western Nepal, with ages suggesting that a significant amount of the sampled sediment has originated from recycling within the Siwalik belt (van der Beek et al. 2006). Recycling is also indicated by the relatively old AFT ages of present-day sediment in the Karnali River (West Nepal) downstream of the Siwaliks, and by long lag times calculated from a published AFT dataset in the distal Bengal fan (van der Beek et al. 2006). The Karnali River sediments are also characterized by lower Na/Si and higher H_2O^+/Si ratios compared to sediments from other trans-Himalayan rivers (where "trans-Himalayan" refers here to rivers crossing the Himalayan range (Lupker at al., 2012a, and Dubille and Lavé, 2015), rather than rivers from the trans-Himalaya region). This unusual chemical composition of Karnali sediments has been attributed to higher contributions of sediments derived from the Siwalik Group, whose Na/Si ratios are comparable (Lupker et al. 2012b).

Here, we first assess which of the central Himalayan catchments recycle the most Upper Siwalik conglomerate by estimating the gravel flux derived from the Siwalik conglomerate based on published detrital ^{10}Be-derived erosion rates (Lupker et al. 2012a) and the mapped extent of Siwalik conglomerates. Subsequently, three end member catchments that vary significantly in terms of contribution from Siwalik conglomerate gravel flux are chosen to explore the impact of conglomerate recycling: the Karnali River which is a mountain-fed river of western Nepal that flows through Siwalik conglomerates over approximately 100 km of its course; the Kosi River of eastern Nepal which is a comparably sized mountain-fed river that recycles no Siwalik conglomerates; and the Mohand River of northern India which is a foothill-fed river that drains exclusively Siwalik sandstones and conglomerate. We hypothesize that significant input of well-rounded, quartzite-dominated clasts from the Siwalik conglomerates should influence the grain size distribution, pebble roundness and lithological content of the river sediment. For each river, we measure downstream variations in grain size, pebble roundness and lithological proportions from exposed gravel bars. In addition, we compare gravel bar lithological data with abrasion calculations based on a model of pebble abrasion with downstream flow distance (Attal and Lavé, 2006) and consider whether conglomerate recycling is required to achieve the lithological proportions forming the gravel bars.

GEOLOGIC AND GEOMORPHIC SETTING

The Himalayan mountain range results from ongoing collision between the Indian and Eurasian plates, which initiated approximately 50 Ma ago (Molnar and Tapponnier, 1975; Philippe and José, 1984; Najman et al. 2010; Bouilhol et al. 2013). Most of the collision has since been absorbed by crustal thickening of the north Indian continental margin, which has shaped the orogen into a broadly east-west trending range, with four major thrust units bounded by major faults (Molnar and Tapponnier, 1975; Yin, 2006) (Figure 1). The four units from top to bottom (broadly equivalent to north to south) are: the Tethyan Himalaya, the Greater Himalayan Crystalline Complex, the Lesser Himalaya, and the Sub-Himalaya (also known as the Siwaliks or Siwalik Hills) (Yin, 2006) (Figure 1). The Main Frontal Thrust (MFT) which bounds the Siwaliks to the south and constitutes the mountain front absorbs ~21+-1.5 mm/yr of convergence between India and South Tibet (Lavé and Avouac, 2000). Tectonic loading during the growth of the Himalaya created the Indo-Gangetic foreland basin, directly south of the Himalayan range. Both basement faulting and variations in lithospheric rigidity are thought to control basin width and large-scale patterns of subsidence (Burbank et al. 1996). Since the formation of the orogen, vast river systems have drained the Himalayan mountains, delivering erosional products of the Himalaya to the basin foredeep (Szulc et al. 2006; van Der Beek et al. 2006), creating multi-storey sandstone and conglomerate bodies (Kumar et al. 2004; Sinha et al. 2014). Basin fill thickness decreases progressively with distance from the mountain front, consistent with asymmetric flexural subsidence caused by thrusting of the overlying orogen (Karner and Watts, 1983; Lyon-Caen and Molnar, 1985; Burbank and Beck, 1991; Burbank, 1992; Burbank et al. 1996). Thin-skinned tectonics associated with the MFT incorporated the poorly consolidated molasse deposits in the hanging wall of frontal structures (Mugnier et al. 2004), forming the Siwalik Hills which locally contain wedge-top basins or ‘duns’ that buffer the sediment delivery to the basin foredeep (Densmore et al. 2016).

The Siwalik Hills are therefore the most southerly and youngest components of the Himalayan mountain range; they are bounded by the Main Boundary Thrust (MBT) to the north (Figure 1).

The Lower-, Middle-, and Upper Siwalik subgroups (Shah, 1977; Hérail & Mascle, 1980) reflect the depositional environments found on the Indo-Gangetic plain (Jain and Sinha, 2003). The Lower Siwaliks consist of mudstones and fine- to medium- grained sandstones with paleosol horizons representing deposition in a distal fine-grained meandering fluvial system. The Middle Siwaliks comprise medium to coarse-grained, cross-bedded sandstones and record the transition from sandy meandering to sandy braided fluvial environments. The Upper Siwaliks are composed of quartzite-rich pebble- to boulder-sized conglomerates (Brozovic and Burbank, 2000; Kumar et al. 2003; Dubille and Lavé, 2015) representing deposition in the gravely proximal alluvial fan (Figure 2). The contact between the Middle and Upper Siwaliks is usually described as abrupt, displaying a sharp increase in grain size by a factor of *ca*. 100 (Dubille and Lavé, 2015). The contact between the Middle and Upper Siwalik is diachronous across the basin. In the western Himalaya, the contact is dated at ca. 2 Ma in the Jammu Hills (Ranga Rao et al. 1988) to 1.5 Ma in the Subathu Basin, west of Dehradun (Tandon and Kumar, 1984); and in central-eastern Nepal, the contact is dated at 3.5-7 Ma along the Muskar Khola (Ojha et al. 2009)(Figure 1). Paleocurrent measurements from Siwalik outcrops indicate that the sediments were deposited by rivers draining in a north-south direction, similar to the present-day rivers of the proximal Indo-Gangetic Plain (Tokuoka et al. 1986; Kumar et al. 2003; Szulc et al. 2006). Due to the steady sedimentation in the Ganga basin, the Siwaliks are considered a comprehensive record of late Himalayan tectonic evolution and climate change in the region (e.g. Najman, 2006).

The large mountain-fed rivers (e.g. Yamuna, Ganga and Karnali) originate from high, glacially-fed source areas, and collect the drainage of multiple major tributaries before entering the plains (Gupta, 1997); there, they evolve into vast alluvial mega-fans (Sinha and Friend, 1994; Sinha et al. 2005; Sinha et al. 2014). Small to medium foothill-fed rivers drain the frontal Siwalik Hills and locally ‘recycle’ the Siwalik deposits (Dubille and Lavé, 2015). In the Plains, they occupy the interfan areas between the mega-fans (Sinha and Friend, 1994; Sinha et al. 2005; Dubille and Lavé, 2015). The gravel-sand transition is found between 10 and 35 km from the mountain front along both foothill-fed and mountain-fed rivers, with the distance generally increasing from east to west, which is thought to result from higher subsidence rates in the east (Dingle et al. 2016).

STUDY AREA

Three end member catchments that vary significantly in terms of the amount of Siwalik conglomerate gravel flux entering the channels are chosen to test the impact of conglomerate recycling on rivers that drain the central Himalaya:

i) The Karnali River is located in western Nepal and is a large (drainage area = ~40,000 km^2) glacially-fed, perennial river with headwaters located high in the Tethyan Himalaya (Figure 1). The Karnali River has two main tributaries, one of which is diverted around the MBT (Gupta, 1997)(Figure 1).The two tributaries converge within the Siwalik Hills. The Main Dun Thrust zone located within the Siwalik Hills between the MBT and MFT comprises a series of relayed thrusts which locally expose the Upper Siwalik conglomerate (Mugnier et al. 1998; DeCelles et al. 1998; Mugnier et al. 1999). The Karnali River drains approximately 240 km^2 of quartzite-rich Siwalik conglomerate before exiting the mountains (Figure 1). In the plains, the Karnali River bifurcates approximately 5 km downstream of the mountain front and reconnects downstream close to the Indian-Nepal border.

ii) The Kosi River of eastern Nepal has the largest catchment of the central Himalaya (~50,000 km^2). It originates in the glacier-covered Tethyan Himalaya and has three major tributaries which join north of the MBT in the Lesser Himalaya before entering the Siwalik Hills. The Kosi River reaches the Plains without flowing through any Upper Siwalik conglomerate. Siwalik exposures are relatively small and are made of Lower-Middle Siwalik sandstone (Schelling, 1992) (Figure 1).

iii) The Mohand River is located in north-west India and is one of many small foothill-fed rivers draining the Mohand anticline to the south. The anticline is formed of Siwalik sediments that were uplifted during displacement on the MFT. Magnetostratigraphic studies from the Kangra Basin (west of Dehradun)(Figure 1) suggest that movement along the MFT in north-west India started approximately 1.9-1.5 Ma ago (Powers et al. 1998; Thakur, 2004). The anticline is bound by the Yamuna River in the west and the Ganga River in the east and is separated from the Lesser Himalayan ranges by a dun valley (Nakata, 1972) (Figure 1). The anticline displays an asymmetric watershed pattern, which is thought to be controlled by the proximity to the MFT. The southern forelimb has larger elongate watersheds in comparison to the back-limb counterparts which are smaller and denser (Singh and Jain, 2009). The Mohand River (drainage area = ~25 km^2) flows from the apex of the anticline and transitions down the forelimb through Upper Siwalik conglomerate and Middle Siwalik sandstone before reaching the Plains (Kumar et al. 2003). Due to the ephemeral nature of the Mohand River, sediment is predominantly transported during the monsoon floods; the river being dry outside these times.

METHODOLOGY

To assess whether conglomerate recycling influences the characteristics of the sediment exported by the Himalayan catchments, we first determine the gravel flux derived exclusively from the Siwalik conglomerate for each of the studied catchments: the Kosi River that recycles no conglomerate, the Karnali River that has significant exposure of Siwalik conglomerate in its lower course, and the small foothill-fed Mohand River whose sediment is exclusively sourced from the Siwalik succession (Figure 1). For each river, we measure and compare downstream variations in grain size, pebble roundness and lithological proportions from exposed gravel bars, and assess whether differences between rivers may reflect conglomerate recycling. This assessment is supported by a model of pebble abrasion: using simple experiments, we test whether the trends observed can be replicated without input of quartzite pebbles from the Siwalik succession.

Gravel flux calculations

To better understand the overall Upper Siwalik conglomerate recycling signal across the Himalayan foreland basin, we first analyze the spatial variations in the relative contribution of recycled Upper Siwalik conglomerate, and the total gravel flux for the main central Himalayan catchments (Yamuna, Ganga, Sharda, Karnali, Gandak and Kosi) (Figure 1). We then focus the rest of our analysis (grain size, lithology and pebble shape) on three chosen catchments (Mohand, Karnali and Kosi) that differ significantly in terms of Upper Siwalik conglomerate flux contribution.

To calculate the total gravel flux derived from the main Himalayan catchments, we estimate the volume of accommodation space available for gravel accumulation between the mountain front and the mapped gravel-sand transition. This calculation follows the approach taken by Dingle et al. (2016) using previously recorded basin subsidence rates combined with distance to the gravel-sand transition, and maximum width of the alluvial fan upstream of the transition (derived from Google Earth imagery) (Dingle et al. 2017) (Table 1). The location of the gravel-sand transition is defined as the point at which the exposed river sediment becomes almost exclusively sand (>95%) (Dubille and Lavé, 2015; Dingle et al. 2016). The calculated volume of accommodation space upstream of the gravel-sand transition to the mountain front is then converted to a total mass of sediment using quartzite density of 2.65 t/m^3 to produce the total gravel flux for each river per year.

In this calculation, we assume that subsidence is steady on a 10^3-10^5 year timescale. In pro-foreland basins such as the Indo-Gangetic Plain, subsidence is a function of the topographic load plus the subduction velocity moderated by the flexural rigidity of the plate (Sinclair and Naylor, 2008). As the convergence velocities between the Indian and Eurasian plate are high, we expect them to dominate the subsidence signal unless the macro-scale topography of the mountain chain varied significantly. Without any evidence of the latter, and with a steady convergence velocity of ~50 mm/yr over the last ~20 Ma (Patriat and Achache, 1984; van Hinsbergen et al. 2011), we envisage subduction velocity to be the dominant control on subsidence. The subsidence rates used in the calculations closely match sediment accumulation rates calculated from Quaternary Ganga Plain sediment cores (Singh et al. 2017; Sinha et al. 1996) and long-term sediment accumulation rates from the Miocene Siwalik Group (Burbank et al. 1996; Sigdel et al. 2011) (Figure 3). This implies that the Ganga Basin is broadly speaking in 'steady state', with sediment routinely filling newly generated accommodation space (Lyon-Caen and Molnar, 1985). Additionally, variable compaction may modify the distribution of surface subsidence (Higgins et al, 2014) but on the timescales considered here, avulsion and migration of gravel channels (e.g. Chakraborty et al., 2010) ensures that the subsurface lithology is dominated by conglomerates upstream of the gravel-sand transition. This is supported by the uniformity of conglomerates in the Upper Siwalik successions which represent the long term record of this setting.

In this calculation, we also assume that the gravel-sand transition remains approximately stable relative to the mountain front, an assumption supported by two observations. Firstly, there is a systematic break in channel gradient at the gravel-sand transition (Dingle et al. 2016), which we would expect to form over significant time scales. Secondly, the long-term record of the gravel-sand transition is represented by the contact between the Middle and Upper Siwaliks. Directly below this contact, thin gravel layers (2-3 meters) relative to the thickness of the succession are often observed within the Middle Siwalik sandstone (Dubille and Lavé, 2015). These gravel 'pulses' likely represent the temporary progradation of the gravel-sand transition into the basin, presumably related to short lived tectonic or climatic events. The fact that these gravel pulses are relatively rare, and that no large sand bodies are observed within the Upper Siwalik conglomerate, suggest that the gravel-sand transition is relatively stable through time. The proportion of the total gravel flux contributed exclusively by erosion of the Upper Siwalik conglomerates is calculated for each catchment using: 1. The percentage of sand versus gravel in Siwalik conglomerate outcrops; 2. the area of Upper Siwalik conglomerate in each catchment (Schelling, 1992; Rautela and Sati, 1996; Mugnier et al. 1999; Yin, 2006; Goswami and Deopa, 2015; and 3. published ^{10}Be-derived erosion rates (Lupker et al. 2012a) (Table 2). The percentage of sand in the Siwalik outcrops was estimated to around 10-15% from photographs of Upper Siwalik outcrops (Figure 2). Sieved volumetric subsurface measurements from present-day gravel bars of the main Himalayan rivers (which are considered modern analogues of the Upper Siwalik conglomerate) corroborate the visual estimate, indicating that the sand component of modern gravel bars also varies between 10 and 15% (Dingle et al. 2016). ^{10}Be concentrations in river sediment across the central Himalaya reveal comparable catchment-wide erosion rates from west to east, with slightly lower rates the furthest west (Yamuna area): the rates are displayed in Table 2 (Lupker et al. 2012a). Previous studies have discussed the reliability of ^{10}Be-derived erosion rates, as ^{10}Be concentrations (used to calculate erosion rates) can be affected by temporal fluctuations in sediment supply upstream of the sample location, and by evacuation times of large sediment deposits such as flood deposits and landslides (Lupker et al. 2012a, Dingle et al. 2018). Sample sites record a factor of 3 variation in erosion rates over consecutive sampling years (Lupker et al. 2012a). These variations have been incorporated into our calculations and are displayed as uncertainties in the estimated flux.

Sediment grain size

Gravel bar grain size measurements are analyzed to assess potential change in the grain size distribution of the river deposits downstream of where Upper Siwalik conglomerate are exposed. Additionally, Upper Siwalik conglomerate grain size is analyzed to compare against the gravel bar grain size measurements.

As rivers exit the mountain onto the Ganga Plain, large gravel bars (0.1-1 km in length) dominate the bed of the rivers. Gravel bar surface grain sizes were measured from the Mohand, Karnali and Kosi rivers over a distance of 30 to 150 km upstream of the gravel-sand transition (Figure 1). Measurements were restricted to parts of the bar that appeared recently mobilised with imbricated gravel, and which reflected the range of grain sizes across the channel. At each site, five to ten photos were taken of the bar surface to use for photo counting. Particle sizes were measured from each photo by overlaying a numeric square grid with 100 nodes and measuring the intermediate *b*-axis of each pebble beneath the nodes, assuming that the *b*-axis is the shortest axis visible on the surface, as pebbles tend to lie with their short axis orthogonal to the surface (Bunte and Abt, 2001; Attal and Lavé, 2006; Whittaker et al. 2011; Dingle et al. 2016). Due to the coarse nature of some of the gravel bars, larger pebbles were often covered by multiple grid nodes. Consistent with the sampling method of Attal et al. (2015), pebbles covering n grid nodes were counted n times, although it is noted that this method may result in overestimation of D_{50} and D_{84} values (50th and 84th percentiles, respectively) (Attal et al. 2015).

Additionally, volumetric subsurface gravel bar measurements were made at some of the sites along the Mohand, Karnali and Kosi Rivers (Mohand = 3, Karnali = 3, Kosi = 6). Subsurface measurements are used to assess whether the surface populations are representative of the subsurface and can therefore be compared to the measurements from Upper Siwalik conglomerate sections which generally represent the subsurface. Volumetric subsurface samples were taken using techniques documented by a number of studies (Attal and Lavé, 2006; Whittaker et al. 2010; Dubille and Lavé, 2015 and Dingle et al. 2016). Surface material was removed from the sampling location to a depth equivalent of the largest pebble observed. Subsequently, 100 – 250 kg of material was excavated and sieved through a series of square-mesh sieves (1, 2 and 4 cm). Pebbles larger than 8 cm were individually weighed and the weight of each fraction was recorded. For pebbles with *b*-axis greater than 8 cm, an approximate diameter was calculated by assuming that the pebble were roughly spherical and had a density of 2,650 kg m^3 (Whittaker et al, 2010; Dingle et al, 2016). As the surface of the gravel bars were generally winnowed, the sand fraction of the sieved material (< 2 mm) was removed from our analysis to compare with the surface measurements. Any sand measurements from the surface samples were also removed, although the amount was generally negligible.

Conglomerate grain size measurements were conducted on the Mohand and the Karnali Upper Siwalik conglomerates (Figure 1). No Upper Siwalik conglomerate is exposed in the Kosi catchment. The Upper Siwalik succession exposed in the studied areas mostly comprises massive several-meter thick beds of poorly consolidated clast-supported conglomerates; individual beds show little evidence of vertical sorting. (Figure 2). Conglomerate grain sizes were measured using the same photographic method as for the surface of the gravel bars. However, in cross section the short axis or *c*-axis of the pebble is more clearly identifiable. A correction was applied to the measurements using the ratio of the *b*- and *c*- axis derived from quartzite pebble measurements from present-day gravel bars (ratio of 1.5, based on 200 quartzite pebble measurements along the Karnali River). This method assumes that the average aspect ratios of the modern and ancient samples are similar (Kellerhals et al. 1975). Bulk-samples were too difficult and dangerous to extract and would have been potentially biased due to few pebbles being fractured and their tendency to fall apart.

The Mohand River Siwalik conglomerate was sampled near the river's watershed (Figure 1). Along the Karnali River, the conglomerate grain size was measured near the tributary junction within the Siwalik Hills (Figure 1). Although the conglomerate measurement sites are limited, Siwalik outcrops along the Mohand anticline (north west India) and along the Churre, Bakeya and Ratu rivers in East Nepal all have similar D_{50} and D_{84} values, and do not display any significant change in grain size up-section (Kumar et al. 2002; Dubille and Lavé, 2015). This suggests that in general the Siwalik conglomerate grain size is relatively homogeneous across the foreland. Slight changes in texture are sometimes observed near the contact between the Middle and Upper Siwalik where thin sand lenses are locally interspersed between the massive conglomerates (Figure 2) (Sigdel et al. 2011).

Lithology

As the Upper Siwalik conglomerate is predominantly composed of quartzite clasts (Brozovic and Burbank, 2000; Kumar et al. 2003; Dubille and Lavé, 2015) lithological proportions of gravel bars are analyzed to test for increases in quartzite pebbles from recycled Siwalik conglomerate as the rivers flow from above the MBT (pre-recycling) and through the Siwalik Hills. Between nine and ten gravel bars located between 150 km upstream of the mountain front and the gravel–sand transition were surveyed along the Mohand, Karnali, and Kosi rivers (Figure 1). At each site, two 25 m transects were positioned near the center of the bar and parallel to the river (Figure 4). The lithology of each pebble was recorded every 0.5 m (Attal and Lavé, 2006; Dingle et al. 2017). The lithological proportions based on the relative number of pebbles derived from the transects are directly comparable to volumetric proportions, with previous studies suggesting surface and subsurface samples yield comparable results (Kellerhals and Bray, 1971; Attal and Lavé, 2006).

Identifying the provenance of gravel bar pebbles is enabled by the contrasting lithologies found in each of the four major structural units of the Himalayan mountain range (Figure 1). The Tethyan Himalayan sequence comprises of marine sedimentary and low-grade meta-sedimentary rocks. The Greater Himalayan Complex contains medium to high-grade metamorphic and igneous rocks including schist, paragneiss, orthogneiss, gabbro and granite. The Lesser Himalayan sequence contains low-grade metasedimentary rocks including phyllite, quartzite, meta-sandstone, marble and dolostone. The Siwalik Group contains Neogene fluvial sandstones and quartzite-rich conglomerates (Kumar et al. 2002; Yin, 2006; Attal and Lavé, 2006; Dubille and Lavé, 2015). Each identified lithology is placed into its corresponding structural unit category. As quartzite could be sourced from all four structural units, it is placed in its own lithological category. No obvious Tethyan Himalayan lithologies were observed on the surveyed gravel bars; but limestone and low-grade metasedimentary pebbles may be sourced from both the Tethyan and Lesser Himalayan successions. Previous work suggests that these lithologies are likely sourced from the Lesser Himalaya, as pebbles sourced from the Tethyan Himalaya are unlikely to survive abrasion during transport to the surveyed bars (Dingle et al. 2017). The Lower-Middle Siwalik sandstone clasts are removed from our analysis because recent roadworks along the frontal Siwalik range (especially in the

Kosi region) has led to increased amounts of Siwalik sandstone entering the channel. No roads are present that could affect the delivery of Siwalik conglomerates in the Karnali and Mohand rivers. Lithological data which includes the Lower-Middle Siwalik sandstone is available in the appendix (Figure A1).

Conglomerate pebble lithology was identified by lithologic counting in a m^2 grid placed on the outcrop. Pebble lithology was recorded for 100 pebbles per grid (Brozovic and Burbank, 2000; Dubille and Lavé, 2015).

Pebble Shape

As the Upper Siwalik conglomerate pebbles are predominately quartzite, we focused on the shape of quartzite pebbles to assess whether pebbles that have experienced recycling (and therefore longer overall transport distance) have a different roundness to those that have not. After recording the lithology along the 25 m transects, the pebbles were placed onto a tarpaulin sheet with their *a-b* plane visible and organized into lithological categories (Figure 4). Photos of the pebbles were taken perpendicular to the tarpaulin sheet. The images were later loaded into a graphics software and the quartzite pebble outlines traced. The traced outlines were loaded into JMicrovision© and the perimeter, area, *b*-axis and *a*-axis of each pebble was extracted.

Using both the perimeter and area, the isoperimetric ratio (IR) of each pebble was calculated using the following relationship, where *A* is area and *P* is perimeter (Szabó et al. 2015):

$$IR = \frac{4\pi A}{P^2} \quad (1)$$

The isoperimetric ratio (IR) is significantly affected by pebble shape (i.e. *b/a* axis ratio): a perfectly rounded elliptic pebble with an axis ratio of 0.5 can have the same IR (0.84) as an angular but more "spherical" pebble (*b/a* = 1) (Figure 5). IR therefore encompasses both angularity and elongation. To isolate the angularity (or roundness) component which is assumed to reflect rounding as a result of fluvial transport, we define a normalized isoperimetric ratio, IR_{norm}, which is the measured IR (equation (1)) divided by the maximum IR the pebble can achieve considering its *b/a* axis ratio (Appendix 2). A perfectly rounded pebble will have $IR_{norm} = 1$, irrelevant of its *b/a* ratio.

Abrasion calculations

Abrasion calculations are used to test whether the concentration of specific lithologies (e.g. quartzite) recorded at the Karnali mountain front can be explained by differential abrasion of mixed lithologies for observed flow distances, or whether the data require the addition of quartzite pebbles as the rivers flow through the Upper Siwalik conglomerate. The gravel bar above the MBT in the Karnali River (Figure 1) was used as a reference. Lithologies were abraded to a chosen sampled gravel bar downstream, using the actual distance between the reference bar (above the MBT) and the chosen gravel bar downstream for the abrasion calculation. A Monte-Carlo approach was developed, whereby each simulation was run 100,000 times using abrasion rates for each lithology chosen randomly within a realistic range based on published abrasion rates for Himalayan lithologies (Attal and Lavé, 2006). This approach was used to explore whether any combination of abrasion rates could produce the same lithological proportions as the observed gravel bar data. The best fit was selected through minimization of ordinary least squares between predicted and measured lithological proportions. The calculations were performed as follows.

The mass loss by abrasion is calculated according to Sternberg's law (Attal and Lavé, 2006):

$$M_x = M_0 e^{-3\alpha x} \quad (2)$$

Where M_x is the mass of gravel remaining at a distance x from the source, M_0 is the mass of gravel at the source and α is the rate of size reduction by abrasion, which is converted into a rate of mass loss by multiplying it by 3 (in km^{-1}) (Attal and Lavé, 2006).

The initial gravel supply at the source is made of n lithologies (with $n = 4$ in our example: quartzite, schist, meta-sedimentary, and crystalline rocks - gneiss, granite, gabbro). The relative proportion of each lithology at the source is given by:

$$(P_0)_i = \frac{(M_0)_i}{\sum_{i=1}^{n}(M_0)_i} \qquad \text{with} \qquad \sum_{i=1}^{n}(P_0)_i = 1. \quad (3)$$

where $(P_0)_i$ is the proportion of gravel from lithology i at the source and $(M_0)_i$ is the mass of gravel from lithology i at the source.

At a distance x from the source, the proportion of lithology i, $(P_x)_i$, is given by:

$$(P_x)_i = \frac{(M_x)_i}{\sum_{i=1}^{n}(M_x)_i} \qquad \text{with} \qquad \sum_{i=1}^{n}(P_x)_i = 1. \quad (4)$$

Because we are interested in the evolution of the relative proportions of gravel from different lithologies, the actual mass of gravel is not relevant. Here we set the initial mass of gravel to 1 kg: $\sum_{i=1}^{n}(M_0)_i = 1$. Therefore, $(M_0)_i = (P_0)_i$.

At distance *x* from the source, the mass of gravel remaining can now be expressed as:

$$\sum_{i=1}^{n} (M_x)_i = \sum_{i=1}^{n} (M_0)_i e^{-3\alpha_i x} = \sum_{i=1}^{n} (P_0)_i e^{-3\alpha_i x} \qquad (5)$$

where α_i is the rate of size reduction by abrasion for lithology *i*. This mass of gravel will here be < 1 kg. The proportion of gravel from lithology *i* at a distance *x* from the source can therefore be calculated through this simple scaling:

$$(P_x)_i = \frac{(M_x)_i}{\sum_{i=1}^{n} (M_x)_i} = \frac{(M_0)_i e^{-3\alpha_i x}}{\sum_{i=1}^{n} (M_0)_i e^{-3\alpha_i x}} = \frac{(P_0)_i e^{-3\alpha_i x}}{\sum_{i=1}^{n} (P_0)_i e^{-3\alpha_i x}} \qquad (6)$$

The use of a single reference gravel bar upstream of the MBT is a significant limitation, imposed by limited access to large parts of the Karnali basin. It implies that the data from this gravel bar is representative of the long-term sediment flux through the Karnali at the sampling point, which is questionable. The implications of this limitation will be discussed along with the results.

RESULTS

Gravel flux

Along the strike of the Himalaya, the total mean gravel flux derived from the main Himalayan catchments varies from 0.9 Mt/yr in the Kosi to 2.6 Mt/yr in the Ganga catchments (Figure 6, Table 3). The Upper Siwalik conglomerate typically accounts for <1% of the total catchment area of the major trans-Himalayan rivers systems which enter the Ganga Plain. Despite this, we find that recycled conglomerate clasts potentially contribute up to 100% of the gravel exported from the Karnali and Gandak catchments and over a quarter of the gravel flux exported from the Ganga River (Figure 6, Table 4). The Yamuna and Sharda catchments have the lowest contribution of conglomerate flux, varying between 0.06 and 0.2 Mt/yr respectively, which equate to 1-25% (Yamuna) and 3-43% (Sharda) of the total gravel flux exported for each catchment. The Kosi River recycles no Upper Siwalik conglomerate. Despite the large uncertainties associated with the calculations, the results indicate that recycling of the Siwalik conglomerate clasts can contribute 1-25%, 7-50%, 3-43%, 37-100% and 35-100% of the total gravel flux for the Yamuna, Ganga, Sharda, Karnali and Gandak rivers, respectively.

Subsequently, the Karnali and Kosi rivers are selected to represent two extreme end members of conglomerate recycling in mountain-fed rivers. The Mohand River, which is a foothill-fed river, is selected as it exclusively drains Siwalik sandstone and conglomerate and therefore its gravel flux is 100% recycled. In the following, we analyze sediment characteristics along these three rivers to assess whether further evidence supports these results, in particular that almost all gravel exported from the Karnali catchment may be sourced from the Siwalik conglomerates.

Grain size

Grain size distributions from the Siwalik conglomerates are compared to the modern river gravels to assess whether the addition of the Upper Siwalik conglomerate influences the grain size distribution of the gravel bars downstream.

Firstly, we compare surface and subsurface measurements at the sites where both measurements were taken to assess whether the surface populations are representative of the subsurface and can therefore be compared to the measurements from Upper Siwalik conglomerate sections (which generally represent the subsurface) (Figure 7). Karnali and Mohand surface and subsurface grain size distributions are very comparable, with the difference between the D_{50} of the surface and subsurface samples ranging between 0.5 and 13.5 mm. The Kosi River surface and subsurface samples are more contrasting, with differences between the D_{50} of the surface and subsurface ranging between 36 and 75 mm (Figure 7). We observe that the Kosi surface measurements can be either coarser or finer than the subsurface (representing differential armoring or amount of sand drape which hides smaller pebbles). As such, gravel bar surface grain sizes are compared to the Upper Siwalik conglomerate grain sizes for the Mohand and Karnali and Kosi rivers, but the Kosi River has additional comparison with available gravel bar subsurface measurements (Figure 8).

The Mohand Upper Siwalik conglomerate exhibits a unimodal grain size distribution, with grain sizes that range between 2 and 160 mm, and a median value of 42 mm (Figure 8). The Mohand River gravel bars also display unimodal grain size distributions. Gravel bar grain sizes vary between 2 and 200 mm, with a few clasts reaching 400 mm where the river passes through the Upper and Middle Siwaliks, creating positively skewed distributions. From the headwaters to the gravel-sand transition, a general downstream grain size fining is observed, with the median grain size decreasing from 56 to 36 mm. Gravel bar grain size distributions from the mountain front (MFT) to the gravel-sand transition closely match that of the Mohand Upper Siwalik conglomerate (Figure 8).

The Upper Siwalik conglomerate surveyed along the Karnali River also exhibits a unimodal grain size distribution, with grain sizes ranging between 2 and 250 mm and a median value of 42 mm (Figure 8). Above the MBT, the gravel bar of the Karnali River exhibits a broad distribution, with sizes varying between 2 and 750 mm and a median value of 220 mm. Boulders larger than 400 mm create a positively skewed distribution. As the Karnali flows across the

Siwalik units, including the Upper Siwalik conglomerate, the gravel bars develop a slightly bimodal to multimodal distribution with a minor increase in the 2-200 mm fraction (Figure 8). Distributions still appear positively skewed but not to the extent of the gravel above the MBT, which indicates an overall reduction in the range of grain sizes. From the mountain front (MFT) to the gravel-sand transition, the Karnali records a clear downstream fining trend, where the grain size distributions narrow and converge towards that of the Karnali Upper Siwalik conglomerate. Median grain size from the MFT to the gravel-sand transition decreases from 148 mm to 46 mm (Figure 8).

Surface data from the Kosi River show weakly bimodal grain size distribution above the MBT, which spans 2 to 400 mm, with a median value of 121 mm (Figure 8). From the MBT to ~10 km downstream from the mountain front, the surface of the gravel bars displays bimodal to multimodal grain size distributions with maximum grain sizes varying between 250 mm and 400 mm and median values that vary between 50 and 120 mm. No obvious downstream fining is observed from above the MBT to 10 km downstream of the mountain front (MFT). Over the last 5 km to the gravel-sand transition, the surface grain size distribution of the gravel bars dramatically fines, and bars exhibit unimodal distributions that span 50 mm to 150 mm, and median values ranging from 10 to 18 mm. Unlike the Karnali and Mohand rivers, the Kosi gravel bar grain size distribution does not converge to a grain size distribution comparable to those recorded elsewhere in the Upper Siwalik conglomerates (Figure 8).

Subsurface data from the Kosi River show similarity to the surface measurements down to the mountain front: above the MBT, the gravel bar displays a bimodal grain size distribution, which spans 2 to 400 mm, with a median of 105 mm. Between the MBT and the MFT, the gravel bar displays a bimodal grain size distribution with grain sizes varying between 100 mm and 300 mm and a median value of 105 mm. However, from 5 km downstream of the mountain front to the gravel-sand transition, the grain size distributions become unimodal in nature and fine, but at a slower rate than the surface: over 10 km, maximum and median grain sizes fine from 300 to 200 mm and from 94 to 91 mm, respectively. The downstream fining is not fast enough to allow the subsurface gravel bar grain size distributions to fully converge to the grain size distribution of the Upper Siwalik conglomerate as recorded by the Mohand and Karnali Rivers (Figure 8).

Lithology

Gravel bar lithological proportions are analyzed to test for increases in quartzite pebbles downstream of the Upper Siwalik conglomerate. The Upper Siwalik conglomerate that outcrops in the Mohand catchment comprise 87% quartzite pebbles, which is comparable to the quartzite content in the gravel bars downstream to the gravel-sand transition (between 70% and 81%) (Figure 9). The Karnali Upper Siwalik conglomerate exposures comprise 94% quartzite pebbles (Figure 9). As the Karnali River flows from above MBT (pre-recycling) to the MFT, the quartzite composition of the gravel bars increases from 31% to 95%, with a recorded increase from 66% to 95% coinciding with the exposure of the Upper Siwalik conglomerate along the last 18 km of the river's course to the MFT. From the MFT to the gravel-sand transition, the proportion of quartzite pebbles in the gravel bars ranges between 81 and 92% with no clear trend, potentially reflecting the natural variability (Figure 9). On average, quartzite clasts make up 84% of the Karnali gravel bar composition from below the MBT to the gravel-sand transition. The Kosi catchment does not contain any Upper Siwalik conglomerate, so no recycled quartzite pebbles can enter the river. From above the MBT to the gravel-sand transition the Kosi River gravel bars contain less than 50% quartzite pebbles, with the average quartzite proportion of all gravel bars equating to 32%, which is significantly less than the Mohand and Karnali rivers (Figure 9).

Abrasion

Lithological data from the Mohand, Karnali and Kosi rivers suggest that conglomerate recycling may be reflected through the lithological proportions of gravel bars downstream of the conglomerate outcrops, resulting in quartzite rich gravel deposits downstream of conglomerate exposures. However, the increase in quartzite proportion from above MBT to the MFT (31% to 95%) in the Karnali River could have an alternative explanation. The deflection of the Karnali River around the MBT adds an additional flow length of ~147 km which could be enough distance for the weaker Himalayan lithologies (gabbro, granite, gneiss, schist) to be completely abraded to sand during transport, resulting in an increased proportion of quartzite pebbles. We use Monte-Carlo abrasion simulation to determine whether: (1) a set of abrasion rates can produce the lithological proportions observed at 18 km upstream of the MFT through the abrasion of the sediment surveyed upstream of the MBT, and (2) whether the increase in quartzite gravel along the last 18 km of the river's course to the MFT can be explained by abrasion alone.

Results from Monte-Carlo abrasion tests indicate that from above the MBT to the next surveyed gravel bar (~ 147 km downstream), abrasion can account for the increase in quartzite (31% - 66%). However, from this point (18 km upstream of the MFT) to the MFT, no combination of realistic abrasion rates can produce the observed increase in quartzite from 66% to 95%. This indicates that abrasion alone cannot account for the increase in quartzite (66%-95%) when the Karnali River flows through the Upper Siwalik conglomerate and that the addition of recycled Upper Siwalik quartzite clasts is needed (Figure 10).

Pebble shape

Analysis of quartzite pebble shape is used to assess whether we can distinguish pebbles sourced from above the MBT to those recycled from Siwalik conglomerates, based on the assumption that the recycled quartzite pebbles may be rounder to those derived from above the MBT from the other structural units (i.e. ‘first generation’). The Mohand River exclusively drains Middle Siwalik sandstone and Upper Siwalik conglomerate, therefore all quartzite pebbles in the Mohand gravel bars are recycled. The Mohand River gravel bars display a negatively skewed distribution of roundness (equation 1) with the bulk of values ranging between 0.97 and 1 and a median value of 0.98, signifying that the majority of the recycled quartzite gravel population is very well-rounded. (Figure 11). Quartzite pebbles analyzed along the Karnali River from downstream of the MBT to the gravel-sand transition also display a negatively skewed distribution with most of the values ranging between 0.95 and 1 and a median of 0.98, which is strikingly similar to the Mohand River (Figure 11). In contrast, the Kosi River quartzite pebbles display a multimodal distribution with three peaks clustering at 0.86, 0.91 and 0.96, and a median of 0.92 which is like that of the Karnali sample upstream of the MBT (Figure 11). No clear downstream trends are identified downstream of the MBT for the Karnali and Kosi Rivers. We can therefore differentiate three populations that can be compared statistically: Karnali above the MBT (pre-recycled), Karnali downstream of the MBT (including recycled component) and Kosi (no recycling). Both independent and Welsh’s t-tests show that there is a statistically significant difference between the Karnali pebble population downstream of the MBT and the Kosi pebble population (Table 5). The t-tests also suggest that the Karnali pebble population above the MBT (pre-recycled) is statistically different from the population below the MBT. However, there is no statistically significant difference between the quartzite pebble population above the MBT in the Karnali River and the quartzite pebble population in the Kosi River, suggesting that unrecycled quartzite pebbles are less well- rounded.

INTERPRETATION OF RESULTS

For each component studied (pebble lithology, grain size, shape), the results indicate that recycling of the Upper Siwalik conglomerate modifies the lithology, grain size and roundness of the gravel entering the Ganga Plain. The Mohand River exemplifies what we would expect in terms of Upper Siwalik conglomerate gravel flux. Typically, Mohand gravel bars have a high percentage of quartzite, a narrow grain size distribution, and well-rounded pebbles, which likely results from the quartzites being transported through the plain multiple times via recycling. Like the Mohand River, the Karnali River displays all these characteristics from the MFT to the gravel-sand transition. The dominant lithology is quartzite, the majority of the sampled quartzites exhibit a high degree of roundness, and the Karnali gravel bar grain size distribution converges to the grain size distribution of the Karnali Upper Siwalik conglomerate. This evidence, combined with our estimates of the gravel flux derived from the Karnali Upper Siwalik conglomerate, suggests that most of the gravel forming the gravel bars downstream of the MFT are likely sourced from the Karnali Upper Siwalik conglomerate. Conversely, the Kosi River gravels bars from the MBT to the gravel-sand transition are composed of different Himalayan lithologies derived from the Greater and Lesser Himalayan structural units. The quartzites sampled along the Kosi gravel bars do not show a high degree of roundness, and the grain size population does not converge onto the grain size distribution of the Upper Siwalik conglomerate. Furthermore, the similarity of the quartzite pebble roundness above the MBT in the Karnali River and the whole quartzite pebble population in the Kosi River suggests that if the Karnali discharged directly onto the Ganga Plain without flowing through the Siwalik units, the quartzite pebbles would be similar in form to the Kosi quartzite pebbles. We therefore conclude that the recycling of the Upper Siwalik conglomerate plays an important role in influencing the grain size distribution, lithological proportions and shape of the gravel exported onto the Ganga Plain from the major Himalayan rivers.

DISCUSSION

How many times can quartzite pebbles be recycled in the foreland?

Ongoing tectonic convergence between the Indian and Eurasian plates (Philippe and José, 1984) has caused rapid proximal basin subsidence which keeps the gravel-sand transition close to the mountain front (10 and 35 km) (Dingle et al. 2016). The combination of the short distance from the mountain front to the gravel-sand transition, the comparably 'short' thrust spacing within the Himalayan foreland (Mugnier et al. 1999), and the low erodibility of quartzite compared to other Himalayan lithologies (Attal and Lavé, 2006) enables quartzite pebbles to potentially be trapped in a continuous conveyor of recycling. Such a process would lead to a progressive increase in abundance of quartzite compared to the softer Himalayan lithologies with each cycle. With an abrasion rate of 0.15 %/km, the mass of a quartzite pebble is expected to decrease by less than 5% during one cycle through the foreland, assuming the pebbles reach the gravel-sand transition. This enables the quartzite pebbles to travel multiple times through the proximal foreland before being abraded into sand. Quartzite pebbles could only be released from the recycling conveyor when either a tectonic or climatic event pushes the gravel front further out into the basin (Burbank et al. 1988; Paola et al. 1992), or if the convergence between the India and Eurasian plates ceases. In this latter case, erosion of the mountains would cause flexural rebound of the orogenic belt and adjacent foreland basin, causing erosion of the proximal foreland deposits, the products of which would be redeposited downstream in the distal foreland (Heller et al. 1988; Sinclair et al. 2017).

From the gravel flux calculations and clast analysis (pebble lithology, grain size, shape), we know that a large proportion of the quartzite pebbles forming the Karnali River gravel bars have been through at least one round of recycling as they are likely derived from the Upper Siwalik conglomerate. However, some western Nepal Siwalik sections located near the Karnali River (exposed along the Macheli Khola, Khutia Khola, Babai Khola and Surai Khola (DeCelles et al. 1998) Figure 1) contain evidence that two rounds of quartzite recycling may have occurred. Siwalik conglomerates in this region (including the Karnali conglomerate in this study (Figure 9)) contain clasts of Siwalik sandstone, which DeCelles et al. (1998) hypothesized were sourced from the hanging wall of the MBT which was then subsequently eroded. If Siwalik sandstone previously outcropped along the MBT hanging wall, it is likely that an Upper Siwalik type conglomerate was also exposed along the MBT and recycled by the paleo-Karnali. However, unlike the Siwalik sandstone, these conglomerate clasts would be indistinguishable in the present-day Upper Siwalik outcrop as they would be formed of clasts from the hinterland.

Implications for the stratigraphic record

In the stratigraphic record, the lithological content of conglomerate layers brings additional information on the eroded landscape upstream (e.g. Abbott and Peterson, 1978; DeCelles, 1988; DeCelles et al. 1993). However, our study of Himalayan river systems illustrates how the original ‘first generation’ lithologic signal of the hinterland (e.g. Kosi River) can be strongly altered by the addition of recycled conglomerate pebbles as rivers pass through the Siwalik Hills (e.g. Karnali River). Due to the varying degrees of conglomerate recycling across strike of the Himalayan foreland (Figure 6), conglomerates in the foreland are expected to record different lithological signals for each river. The Karnali catchment, and most foothill derived rivers (e.g. Mohand River), would produce quartzite-rich conglomerate deposits, whereas rivers which recycle less Siwalik conglomerate (e.g. Yamuna, Sharda and Kosi) would produce a conglomerate formed from a variety of clasts, with varying degrees of roundness (Figure 12). Furthermore, it is important to consider the locus and episodicity of sediment supply to rivers. Recent work has shown that Himalayan seismicity can involve blind earthquakes (up to Mw ~ 7.8) clustering at depth along the basal detachment fault, and infrequent punctuated great earthquakes (Mw 8+) which propagate up to the MFT (Dal Zilio et al. 2019) which lies between the Siwalik group and the Ganga Plain (Figure 1). Because earthquakes can drive pulses of sediment through landsliding (e.g. Yanites et al. 2010; Huang and Fan. 2013), with landsliding focused in areas of most intense shaking, we would expect, in rivers that recycle a moderate amount of Upper Siwalik conglomerate, that the lithological content of the gravel entering the Plains would be more representative of the catchment geology following phases of deep blind earthquakes. However, during phases of intense seismicity along the MFT, we would expect an increased amount of Siwalik conglomerates delivered to the proximal Ganga Plain (Dingle et al. 2017). This would create episodic up-section changes in lithological content, as the quarzitic conglomerate pebbles would overwhelm and reduce the hinterland lithological signal with each punctuated tectonic event along the MFT (Figure 12). Similarly, extreme storm events are capable of generating localized erosion in a catchment and subsequent sediment delivery downstream (e.g. Devrani et al., 2015). Intense orographic enhancement of precipitation and associated storms localized along the abrupt topographic gradient formed by the southern Lesser Himalaya (directly north of the Siwalik Hills) (Bookhagen et al. 2005; Bookhagen and Burbank, 2006; Anders et al. 2006) could also yield disproportionately high amounts of recycled quartzite pebbles relative to the catchment as a whole.

Implications for river processes and behavior

The sediment characteristics of rivers that drain mountain ranges determines a channels tendency to aggrade or incise, aspects of its morphology and downstream sediment fining rates. Changes in median grain sizes and distributions determine rates of sediment entrainment and grain size change towards and at the gravel-sand transition (Duller et al. 2010). An increase in the spread of grain sizes in the sediment supply entering a basin (e.g. Kosi, first generation sediment supply dominated) can generate a greater rate of down-system grain size fining, compared to rivers with a more uniform grain size distribution (e.g. Mohand and Karnali) (Duller et al. 2010). Therefore, the degree of recycling is likely to impact along strike variations in fining trends across a basin. Due to the poorly consolidated nature of the Upper Siwalik conglomerate (Dubille and Lavé, 2015), any tectonic activity associated with the MFT could also add large amounts of recycled conglomerate material to the nearby channels via landsliding. A sudden increase in the volume of sediment entering the foreland could cause a localized decrease in the rate of grain size fining (Paola et al. 1992, Duller et al. 2010) and morphological changes such as localized channel aggradation (Eaton and Church 2009, Yanites et al. 2010, Keefer 1999), channel widening, and increased channel braiding (Carson 1984, Harvey 1991). Grain size and shape also impact the selective entrainment of pebbles (Komar and Li, 1986). The Mohand and Karnali river deposits (downstream of the MFT) are formed of clasts which have a narrow grain size distribution, are well sorted, and predominately ellipsoidal in shape, which facilitates imbrication. This combination may make the dominant quartzite pebbles of the Mohand and Karnali rivers difficult to entrain (Komar and Li, 1986). In rivers which recycle less Upper Siwalik conglomerate (i.e. Kosi) there is a wider grain size distribution and the clasts are more angular. This may encourage differential entrainment thresholds along an individual gravel bar and the formation of cluster bedforms which are common in poorly sorted gravel-bed channels with differing clast lithologies like the Kosi River (Brayshaw, 1983; Brayshaw, 1985; Dal Cin, 1986). Such bedforms can account for phenomena such as discontinuous particle movement and variations in the composition of bed load during discharge events (Brayshaw, 1983; Brayshaw, 1985).

Application to other foreland basins

Here we have identified recycling of foreland deposits as a process which should be considered in many foreland basin settings when interpreting provenance, grain size and river morphology data. This applies particularly where: 1. Thin-skinned tectonics allow relatively fast foreland accretion to occur at the mountain front. The thin-skinned nature of the thrusting makes thrusted foreland material available for recycling and ensures limited transformation of the sediment (i.e. un-metamorphosed). 2. The presence of marked contrasts in rock strength in the lithologies of the upstream catchment. For example, a catchment which contains quartzite would ultimately form foreland deposits that are quartzite-rich (e.g. Himalaya). These deposits are then recycled via thrusting and erosion which further dilutes the full spectrum of lithologies in the upstream catchment. This process is exemplified in the Himalaya and in conglomerates outcropping in Serra de La Llena (north-east Spain; Colombo, 1994) and in Otago (New Zealand; Youngson and Craw, 1996). Any combination of the two conditions (thin-skinned tectonics; contrasting catchment geology rock strength) would cause the recycling signal to occur to varying degrees. Our work shows that the coarse fraction of the stratigraphic record can be extremely biased towards small parts of the catchment where there is recycling. Earthquake-induced shaking or extreme storms localised on areas where quartzite-rich conglomerates are exposed will lead to significant export of gravel to the foreland basin, even if the conglomerate area represents a small fraction of the catchment area. Such gravel pulses will likely be locked in the stratigraphic record. Events of similar magnitude over the rest of the catchment will not necessarily leave a trace in the coarse fraction of the stratigraphic record. Caution must therefore be exercised when interpreting pulses of gravel in stratigraphy in terms of tectonic or climatic driver.

Finally, pebble roundness is commonly interpreted as reflecting travel distance (Szabó et al. 2015) and therefore used as a proxy for the size of a catchment. An abrupt increase in pebble roundness in conglomeratic stratigraphy may be interpreted as a change in catchment size, increasing the distance between the source areas and the depocentre. However, exposure and recycling of conglomerates rich in well-rounded quartzite pebbles could produce a similar signal without a change in catchment size.

CONCLUSION

The Upper Siwalik conglomerates comprise poorly consolidated, rounded clasts, and the dominant clast lithology is quartzite. Mass balance calculations reveal that the Upper Siwalik conglomerate can contribute a significant proportion of the total gravel flux exported from the main Himalayan catchments (up to 100%) despite forming <1% of the catchment geology in trans-Himalayan catchments.

This study highlights that the gravel exported from the hinterland onto the Indo-Gangetic Plain can be substantially altered by the recycling of older, structurally exhumed foreland deposits. Our three chosen catchments (Mohand, Karnali and Kosi) exhibit substantial differences in exported gravel characteristics (grain size, lithology and pebble shape) which reflect how much recycled Upper Siwalik conglomerate pebbles they receive. Recycling of Upper Siwalik conglomerates modifies the lithological content of the gravel bars by enriching the deposits with quartzite pebbles. Recycling also transforms the grain size distribution of the fluvial deposits downstream of the Siwalik outcrops, whereby the gravel bar grain size distribution converges to that of the Upper Siwalik conglomerate. Furthermore, pebble roundness is greater in catchments with a recycled quartzite component, possibly because the recycled quartzites have been transported multiple times through the plains following structural exhumation, becoming less angular with each cycle. Due to the proximity of the gravel sand transition to the mountain front, the narrow thrust spacing in the Himalayan foreland and the resistant nature of the recycled quartzite pebbles, recycled pebbles are likely to be trapped in a continuous conveyor of recycling, rarely escaping the proximal foreland.

APPENDIX

The Appendix contains Appendix 1 (Figure A1), Appendix 2 (Figure A2), and three tables (Tables A1, A2, A3).

Appendix 1: Pebble lithologies documented on exposed gravel bars

The Lower-Middle Siwalik sandstone clasts are removed from our lithological analysis (Figure 9) because recent roadworks along the frontal Siwalik range (especially in the Kosi region) has led to increased amounts of Siwalik sandstone entering the channel. Lithological data which includes the Lower-Middle Siwalik sandstone is displayed in Figure A1.

Appendix 2: calculation of the normalized Isoperimetric Ratio.

The isoperimetric Ratio (equation (1)) has been used to quantitatively characterize pebble shape evolution (e.g., Szabó et al. 2015). However, this parameter is sensitive to the elongation (or axis ratio) of pebbles (Figure 5): it can be demonstrated, by calculating the area and perimeter of an ellipse, that a perfectly rounded elliptic pebble will have an IR $<$ 1. The red curves in

Figure 5 and Figure A2(A) have been drawn by calculating the IR of perfect ellipses with varying axis ratios. The data closely track the curves, confirming the theory. To isolate the roundness (or angularity) component from the elongation component of IR, we define a normalized isoperimetric ratio IR_{norm}, which is the measured IR of a pebble divided by the IR of a perfect ellipse of similar axis ratio. IR_{norm} reflects a pebble's roundness (or angularity), irrelevant of its axis ratio, as demonstrated in Figure A2(B). Perfectly rounded pebble have $IR_{norm} = 1$. We note that IR_{norm} is independent of pebble size, suggesting the rounding process is not size-selective.

Some values of IR_{norm} are greater than one, which is theoretically impossible. We attribute these to uncertainties on measurements of the *a* and *b* ratios from photos: small errors (a few mm) can lead to underestimation of the a/b ratio and therefore underestimation of the maximum IR a pebble can achieve, leading to IR_{norm} values greater than 1. We also wonder whether, in some rare cases, complex pebble shapes may lead to situations where IR_{norm} can exceed 1. Finally, it is worth noticing that the ellipse appears to be the optimal shape for maximum IR for aspect ratios > 0.4 (which applies to all of our pebbles) but that for low aspect ratios (< 0.2), some shapes can achieve greater IR than an ellipse. For example, a pebble with an aspect ratio of 0.2 whose shape is characterized by the equation of the standard ellipse with an exponent 4 instead of 2 (more "rectangular" shape) has an IR 6 % greater than the standard ellipse ($IR_{norm} = 1.06$). It is important to consider this point when trying to apply the method to highly elongated pebbles.

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FIGURE CAPTIONS

FIGURE 1. Catchment geology digitized and placed on a 90 m SRTM DEM (Yin, 2006; Schelling, 1992, Mugnier et al. 1999, Rautela and Sati, 1996, Goswami and Deopa, 2015). Map includes: Siwalik exposures mentioned in text or used in analysis (purple lines) (JH - Jammu Hill section, K&J - Kangra and Jawalamukhi sections, SB - Subathu basin section, MaK - Macheli Khola section, KK - Khutia Khola section, KS - Karnali section, BbK - Babai Khola section, SK - Surai Khola section, BK - Bakeya Khola section, MK - Muskar Khola section (Tandon and Kumar, 1984; Ranga Rao et al. 1988; Meigs et al. 1995; Burbank et al. 1996; DeCelles et al, 1998; Brozovic and Burbank, 2000; Ojha et al. 2009; Sigdel et al. 2011). Localities of core used in figure 3 (orange stars) (Sinha et al. 1996; Singh et al. 2017). Localities of ^{10}Be samples used in the conglomerate gravel flux calculations (blue circles) (Lupker et al. 2012a). Boxes A), B) and C) are detailed maps of The Mohand, Karnali and Kosi rivers near the mountain front, respectively. Red circles represent conglomerate sampling locations. White starts indicate gravel bar sampling localities.

FIGURE 2. Photographs of the Upper Siwalik conglomerate exposed along the Karnali River. A) A typical exposed section of the Siwalik conglomerate. Beds are generally several meters thick, with rare sand lenses. B) Close up of the Upper Siwalik conglomerate. Note the well-rounded nature of the quartzite clasts forming the conglomerate.

FIGURE 3. Subsidence rates used in the gravel flux calculations (Dingle et al. 2016) (grey diamond), plotted alongside sediment accumulation rates calculated from Quaternary Ganga Plain sediment core (red triangle) (Singh et al. 2017 (MNK6, SRH5); Sinha et al. 1996 (S3H4, S3H6, S15H3/4, S33H4/5, S32H5/6, S32H6/7), and long-term sediment accumulation rates from the Miocene Siwalik Group (purple circle) (Burbank et al. 1996 (Surai Khola section, Bakiya Khola section, Jawalamukni section); Sigdel et al. 2011 (Karnali section)). Locations of Ganga Plain sediment core and Siwalik sections are located on Figure 1.

FIGURE 4. Characterization of lithological content and pebble shape. A) Transect method used to pick clasts for lithological identification. B) Photograph of quartzite clasts placed on a tarpaulin sheet. Outlines of pebbles were later traced and loaded into JMicrovision© software to analyze pebble roundness (IR_{norm}).

FIGURE 5: Demonstration of the influence of pebble elongation (*b/a* ratio) on the isoperimetric ratio (IR). The maximum value of IR a pebble can achieve depends on its axis ratio. As a result, a perfectly rounded elliptic pebble with an axis ratio of 0.5 can have the same IR value (0.84) as an angular spherical pebble. The red line represent the theoretical maximum IR as a function of the axis ratio (see Appendix A).

FIGURE 6. A) Estimates of total gravel flux derived from the main Himalayan catchments (black), and contribution from the Upper Siwalik conglomerate for the same catchments (orange). The former is based on subsidence data and position of the gravel-sand transition whereas the latter is derived from applying ^{10}Be derived erosion rates over the exposed Siwalik

conglomerate area and accounting for the portion of sand vs gravel within the exposure. B) Estimates of gravel flux per unit catchment area. Error bars associated with catchment total flux (black) reflect the differences in accommodation space available for sediment to accumulate under maximum and minimum subsidence rates (Dingle et al. 2017). Error bars associated with Upper Siwalik gravel flux (orange) represent the uncertainties in sand vs gravel estimates in the conglomerate exposure, and in and ^{10}Be derived erosion rates (Lupker et al. 2012a). Numbers correspond to ^{10}Be derived erosion (mm/yr) rates used in the calculations.

FIGURE 7. Cumulative grain size distributions of the surface (colored lines) and subsurface (black lines) grain size measurements with accompanying D50 values for the Mohand, Karnali and Kosi rivers. Mohand and Karnali plots (A- F) display good correlation between the surface and subsurface samples. Kosi samples (G-I) do not show good correlation between the surface and subsurface grain sizes. Six Kosi subsurface samples are available, plotted are the three most contrasting.

FIGURE 8. Kernel density estimation (KDE) plot of surface (A, B, C) and subsurface (D) grain size measurements of surveyed gravel bars for the Mohand (A), Karnali (B) and Kosi (C, D) rivers (coloured plots). The gravel bar KDE plots are overlain by corresponding Upper Siwalik conglomerate KDE plot (grey) for comparison. The Kosi River gravel bar KDE plots has the Karnali conglomerate KDE plot overlain for comparison. Distances are relative to the mountain front, so negative distances are upstream of the mountain front.

FIGURE 9. Pebble lithologies documented on exposed gravel bars along the A) Mohand, B) Karnali and C) Kosi rivers. Distances are relative to the mountain front, so negative distances are upstream of the mountain front. Lower-Middle Siwalik sandstone has been removed from the gravel bar plots. Conglomerate lithologies are shown for the Mohand and Karnali Rivers (cong).

FIGURE 10. Karnali gravel bar lithological proportions overlain by the modelled 'best fit quartzite proportion'. Monte-Carlo abrasion calculations suggest that from above the MBT to the next surveyed gravel bar (~ 147 km) downstream, abrasion can account of the increase in quartzite. However, abrasion cannot account for the increase in quartzite further downstream: under this scenario quartzite proportion is expected to slowly increase from 72 to 74% over the 52 km from the site 18 km upstream of the MFT to the gravel-sand transition (red line).

FIGURE 11. A) Violin plot of quartzite pebble normalized Isoperimetric Ratio (IR_{norm}) of all the gravel bars downstream of the MBT for each river (Mohand, Karnali, & Kosi). Red line represents the median of the distribution. Roundness (IR_{norm}) of pebbles increases up to 1. B) Evolution downstream of pebble roundness (IR_{norm}) for the Karnali and Kosi rivers. Distances are relative to the mountain front, so negative distances are upstream of the mountain front. Dashed red line highlights the similarity between the Karnali gravel bar sample above the MBT and the Kosi River samples.

FIGURE 12. Cartoon illustrating how conglomerate recycling modifies the lithology, grain size and shape of gravel entering the Ganga Plain. The Upper Siwalik conglomerate is quartzite rich,

has a distinctive unimodal grain size distribution and well-rounded quartzite clasts. Catchments which recycle Upper Siwalik conglomerate export quartzite rich sediment with rounder clasts and a unimodal grain size distribution that reflects the Upper Siwalik grain size distribution. Catchments which recycle little/no Upper Siwalik conglomerate export sediment with mixed hinterland lithologies, a more varied grain size distribution and individual quartzite clasts appear less well-rounded.

FIGURE A1. Pebble lithologies (including Lower-Middle Siwalik sandstone) documented on exposed gravel bars along the A) Mohand, B) Karnali and C) Kosi rivers. Distances are relative to the mountain front, so negative distances are upstream of the mountain front.

Figure A2. A) Relationship between isoperimetric ratio (IR) and axes ratio for quartzite pebbles in the Mohand, Karnali and Kosi rivers. Red line represents theoretical maximum IR as a function of the axis ratio. B) Relationship between our newly defined normalized isoperimetric ratio (IR_{norm}) and axis ratio for the three rivers. IR_{norm} isolates the roundness component from the elongation component: perfectly rounded pebbles are characterised by $IR_{norm} = 1$ irrelevant of their axis ratio. C) Relationship between IR_{norm} and quartzite pebble size (b-axis): there is no correlation between pebble size and roundness.

TABLE CAPTIONS

TABLE 1. Data table 1 displays data used to calculate the total gravel flux for each catchment. Catchment areas are derived from 90 m Shuttle Radar Topography Mission Digital Elevation model. Distances to the gravel-sand transition (except for the Karnali) are taken from previously

published work (Dingle et al. 2016; Dingle et al. 2017). Subsidence rates were taken from previously published work (Dingle et al. 2017).

TABLE 2. Data table 2 displays data used to calculate gravel flux derived from the Upper Siwalik conglomerate for each catchment. Upper Siwalik conglomerate areas are derived from the mapped extent of the Siwalik conglomerates placed onto a 90 m Shuttle Radar Topography Mission Digital Elevation Model. Denudation rates are taken from previously published work (Lupker et al, 2012a). Denudation rates are from samples located nearest to the mountain outlet for each catchment. Some catchments have multiple samples collected over consecutive years; the average rate was calculated using all samples from consecutive years for each catchment.

TABLE 3. Table 3 displays calculated accommodation space generated per year for each catchment. Accommodation space generated per year is the product of fan width, distance between the mountain front and the gravel-sand transition and subsidence rates (Dingle et al. 2017). Minimum, average and maximum total gravel fluxes are calculated by multiplying the accommodation space generated per year by the density of quartzite (2.65 tonnes m^3) (Dingle et al. 2017).

TABLE 4. Data table 4 displays calculated gravel flux for the Upper Siwalik conglomerate. Upper Siwalik conglomerate flux per year is the product of bedload percentage (85 – 90 %) derived from photographs of Upper Siwalik outcrops and sieved volumetric subsurface measurements from present-day gravel bars (Dingle et al. 2016), published denudation rates (Lupker et al, 2012a) and the mapped area of Upper Siwalik exposure in each catchment.

TABLE 5. Results of statistical comparison of three pebble populations in terms of roundness (IR_{norm}). The three populations are: Karnali above the MBT (pre-recycled), Karnali downstream of the MBT (including recycled component) and Kosi (no recycling). DoF is degree of freedom. We performed tests using both independent t-test and Welsh's t-test. The latter was performed as it is more indicated in the case of non-equality of variances (which is the case in two of the three comparisons). We note the populations are not normally distributed, in particular the Karnali downstream of the MBT (very high median of 0.98 but theoretical maximum truncated at 1.00, see Figure 9A). However, the populations are large enough, in particular the Karnali downstream, to allow sampled population for t-tests to be normal. Using the threshold *p* value of 0.05, we find no statistically significant difference between the Karnali upstream of the MBT and the Kosi populations. Other comparisons yield statistically significant differences.

TABLE A1. Sample localities along the Mohand River.

TABLE A2. Sample localities along the Karnali River.

TABLE A3. Sample localities along the Kosi River.